Cooperative Localization of Drones by using Interval Methods

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Introduction

In this paper, we address the problem of cooperative pose estimation [1] in a group of N unmanned aerial vehicles (UAV), each equipped with a camera that sees landmarks with known positions. The UAVs communicate, exchange poses and measure distances with neighbours and a base station. Our aim is to compute the pose domain of each robot assuming the errors on measurements are bounded.

Single robot pose estimation

Each robot first estimates its pose domain $\mathbf{r} = (x, y, z, \phi, \theta, \psi)$ using camera and base distance constraints. To get the camera constraints, the perspective projection equation (Eq. (1), pinhole camera model) of a 3D world point ${}^{w}\mathbf{X}$ in the camera frame represented in normalized coordinates $\mathbf{x} = ({}^{c}x, {}^{c}y)$ is used (see [2] in camera only case).

$$\mathbf{x} = \mathbf{\Pi}\, {}^{c}\mathbf{T}_{r}\, {}^{r}\mathbf{T}_{w}(\mathbf{r})\, {}^{w}\mathbf{X} \tag{1}$$

with ${}^{r}\mathbf{T}_{w}$ the unknown transformation matrix between the world reference frame and a frame attached to the robot and ${}^{c}\mathbf{T}_{r}$ is the known rigid transformation between the camera and the robot frames. Equation (1) is applied for each visible landmark ${}^{w}\mathbf{X}_{i}$ $(i \in 1..m)$ and the following constraints can be derived

$$C_i : \begin{cases} ({}^cX_i, {}^cY_i, {}^cZ_i) = {}^c\mathbf{T}_r\, {}^r\mathbf{T}_w(\mathbf{r})\, {}^w\mathbf{X}_i \\ {}^cx_i = \frac{{}^cX_i}{{}^cZ_i}, {}^c y_i = \frac{{}^cY_i}{{}^cZ_i}, \\ {}^cx_i \in [{}^cx_i],\ {}^cy_i \in [{}^cy_i], {}^cZ_i \ > \ 0. \end{cases} \tag{2}$$

The image/range-based pose estimation problem is then defined as a constraint satisfaction problem (CSP)

$$\mathcal{H} : \begin{pmatrix} \mathbf{r} \in [\mathbf{r}], \\ \{C_i,\ i \in 1...m\} \\ C_{dist} \end{pmatrix}$$

Where C_{dist} is the additional distance constraint between the robot position $p = (x, y, z)$ and the base station B used to get a tighter pose estimate

$$C_{dist} : d = \|\mathbf{p} - \mathbf{b}\|_2\,, \quad d \in [d]$$

with $\mathbf{b}$ the known position of the base station.

A robot R_k computes a domain in a form of an outer subpaving $\mathbb{S}^+_{\mathbf{r}_k}$, that contains all the feasible poses, using SIVIA [3] to solve $\mathcal{H}$.

Robots cooperation: data exchange

At each time step, once the pose domain $\mathbb{S}^+_{\mathbf{r}_k}$ is computed, the robot exchanges the bounding box of its position domain $[\mathbf{p}_k] = \square\, \mathrm{proj}_{\mathbf{p}}\, \mathbb{S}^+_{\mathbf{r}_k}$, where $\square$ is the bounding box operator, and $\mathrm{proj}_{\mathbf{p}}$ is the projection onto the position space. The position $[\mathbf{p}_k]$ is transmitted to all neighboring robots R_j, $j \in \mathcal{N}(k)$, and the distances $d_{k,j}$ between R_k and R_j are simultaneously measured (with $\mathcal{N}(k)$ the neighbours of R_k).

At reception of information (position boxes $[\mathbf{p}_j]$ and bounded-error distances measurements $[d_{k,j}]$) from neighboring robots, R_k tries to refine its actual pose domain, by propagating the new distance constraints between R_k and each of its neighbours. A CSP is also built and SIVIA is used to refine the pose domain.

Experimental results

The proposed method has been tested with data acquired on Parrot AR-Drone2 UAV, with 5 landmarks represented by AprilTag markers. The image measurement error bounds are set to ± 0.5 px and the range measurement error is assumed to be within ± 5 cm.

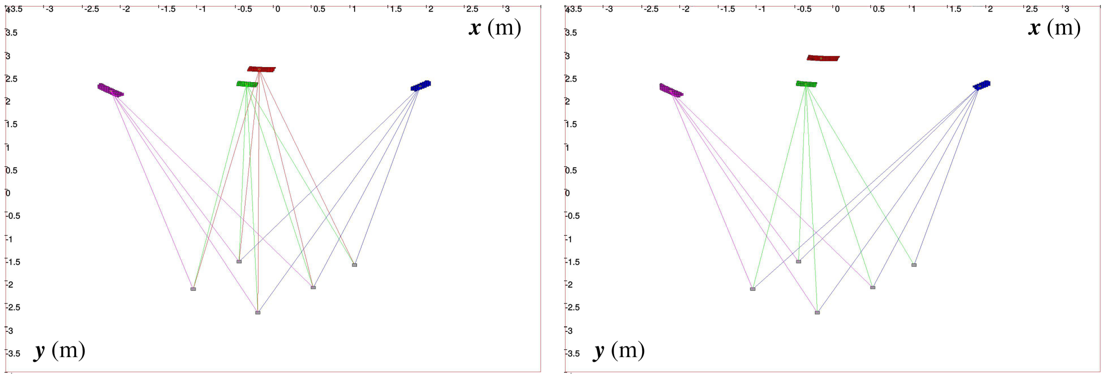

Figure 1: Pose domain for 4 robots.

The left part of Fig. 1 shows subpavings obtained when all 4 robots observe the 5 landmarks (full visibility case). The image on the right of Fig. 1 shows how cooperative localization reduces the feasible pose domain when one robot (in red) cannot clearly see the landmarks, by propagating position information of the neighbours. The average horizontal position error is less than 5 cm for each of the drones.

References

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[**3**] L. Jaulin and E. Walter, Set inversion via interval analysis for nonlinear bounded-error estimation, *Automatica*, 29, 1053-1064, 1993.